The radio properties of radio-quiet quasars

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Abstract. Although radio-quiet quasars (RQQs), which constitute the majority of optically-identified quasar samples, are by no means radio silent the properties of their radio emission are only poorly understood. We present the results of a multi-frequency VLA study of 27 low-redshift RQQs. In general, we find that the properties of the radio sources in RQQs are consistent with them being weak, small-scale (~ 1 kpc) jets similar to those observed in nearby Seyfert galaxies. We conclude that a significant fraction of the radio emission in RQQs is directly associated with the central engine and is not a result of stellar processes in the surrounding galaxy. There appears to be no difference between the radio properties of RQQs in elliptical and disc galaxies, implying that the relationship between the host galaxy and the 'radio loudness' of the active nucleus is not straightforward.

1 Introduction

Studies of nearby active galaxies have shown that the radio-loud objects (*ie* radio galaxies) are invariably elliptical systems whereas the radio-quiets (Seyferts) tend to be spirals, suggesting that it is some property of gas-rich disc galaxies which inhibits the formation of large, powerful radio sources. Two factors have encouraged the extension of this result to the higher redshifts and larger nuclear luminosities typical of quasars: the success of Unified Schemes which link radio galaxies and radio-loud quasars (RLQs) via beaming effects and viewing angle and the fact that Seyfert 1 nuclei and radio-quiet quasars (RQQs) form a continuous sequence in terms of their optical luminosities and have identical emission line characteristics. Thus we have a picture in which RLQs occur in elliptical galaxies whilst RQQs are found in discs.

However, recent studies have shown that quasars occur in a wide variety of environments (*eg* Bahcall *et al.* 1997). In particular it seems that *not all* RQQs lie in disc systems, with as many as 50% occurring in elliptical galaxies (*eg* Véron-Cetty & Woltjer 1990). Indeed, there is some evidence that elliptical galaxies might account for all of the most optically luminous RQQs (Taylor *et al.* 1996). Clearly the simple 'radio-loud $\equiv$ elliptical, radio-quiet $\equiv$ disc' picture can no longer be supported, and it has become more important than ever to determine in what respects radio-quiet quasars are different from their radio-loud counterparts. Unfortunately, the most obvious wavelength regime in which they differ - the radio - is also the regime in which least is known about the properties

of RQQs. Most radio surveys of optically-selected quasar samples have lacked the sensitivity to detect the majority of radio-quiet objects, and have provided only limited information on their radio structure and spectral index.

To remedy this situation we embarked on a multi-frequency, high-resolution radio survey of 27 low-redshift ($0.1 \leq z \leq 0.3$), low-luminosity ($M_V > -26$) RQQs using the Very Large Array (VLA). Observations were made in 'A' configuration at 1.4, 4.8 and 8.4 GHz, with angular resolutions of 1.4, 0.4 and 0.24″ respectively, and radio emission was detected in 75% of the quasars. The survey will be discussed in more detail by Kukula *et al.* (1997).

2 Results of the survey

A principal goal of the survey was to investigate the origin of the radio emission in RQQs and to attempt to distinguish between radio emission produced by stellar processes (*eg* circumnuclear starburst regions) in the body of the host galaxy and emission which is directly associated with the quasar (*eg* radio jets). Our findings can be summarized as follows:

(1) In the majority of objects we detect an unresolved (≤ 1 kpc) radio component which is coincident with the optical position of the quasar.

(2) The radio spectral indices of the RQQs are generally steep ($\alpha \sim 0.7$, where $S \propto \nu^{-\alpha}$), although two objects, which also exhibit unusually large radio luminosities and optical variability, have flat radio spectra. Following Falcke, Sherwood & Patnaik (1996) we interpret these flat-spectrum objects as RQQs in which a relativistic jet is closely aligned to the line of sight, leading to doppler boosting of the radio emission.

(3) Lower limits on the brightness temperatures of the radio sources place them at the upper end of the range expected for emission related to stellar processes ($T_B \sim 10^5$ K). In many objects the brightness temperature is almost certainly many orders of magnitude greater than this, in which case the radio emission *cannot* be produced by a starburst. Observations with greater angular resolution will be required in order to confirm these results.

(4) In five objects we are able to resolve radio structure, which takes the form of double, triple and linear sources on scales of a few kiloparsecs. These images resemble early, low-resolution maps of nearby Seyfert nuclei - objects which have since been shown to contain small-scale (≤ 1 kpc), highly-collimated radio jets. The current maps could therefore be taken as evidence that collimated ejection of radio plasma from the central engine is also occurring in RQQs but high-resolution VLBI observations will be necessary in order to confirm this interpretation.

(5) The distribution of radio luminosities in the RQQ sample forms a natural extension to that of Seyfert 1 nuclei. There appears to be a correlation between radio luminosity and the optical absolute magnitude of the quasar, implying a close relationship between the central engine and the mechanism responsible for the bulk of the radio emission.

We therefore conclude that in the majority of RQQs a significant fraction of the overall radio emission comes from a compact nuclear source which is directly associated with the quasar's central engine. By analogy with Seyfert galaxies this nuclear source probably takes the form of a small-scale radio jet, qualitatively similar to the more powerful jets observed in RLQs and radio galaxies.

3 Radio emission and the hosts of RQQs

Seventeen of the RQQs in the present sample were also included in our near-infrared imaging study of quasar hosts (Taylor *et al.* 1996; described elsewhere in this volume by Kukula *et al.*). These observations showed that slightly less than half of the RQQs occur in galaxies in which the dominant stellar component has a spheroidal rather than an exponential (disc) distribution.

We were therefore able to carry out a study of the relationship between the host morphology and the radio properties of the AGN and to investigate the extent to which the radio sources in RQQs with spheroidal hosts could be distinguished from those in discs. The AGN traditionally associated with elliptical hosts (*ie* radio galaxies and RLQs) produce large, powerful radio sources and this suggests that the RQQs in elliptical galaxies, whilst technically 'radio quiet', might still harbour radio sources which differ in size and luminosity from those in disc galaxies.

However, in our sample we were able to find *no* clear separation between the radio properties of the two types of radio-quiet quasar. The RQQs with elliptical hosts *do not* contain larger or more luminous radio sources than those in disc galaxies. Both types of RQQ are equally likely to contain extended radio structure and to show evidence for collimated radio jets. The radio sources in elliptical galaxies show no tendency to have flatter spectra than those in discs (as might have been expected if the jets in elliptical galaxies are more likely to be relativistic).

Although the current sample is small, and is limited to RQQs of relatively low optical luminosity, our radio survey clearly demonstrates that having an elliptical host does not automatically confer a large radio luminosity on the active nucleus. A significant number of ellipticals with active nuclei are *not* producing large, powerful radio sources but contain small, weak sources which appear to be identical to those in disc systems. Further, more detailed studies of the host galaxies will be required in order to determine if and how these ellipticals differ from those containing radio loud AGN.

References

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